Two-layer slotted-waveguide antenna array with broad reflection/gain bandwidth at millimetre-wave frequencies

S.-S. Oh, J.-W. Lee, M.-S. Song and Y.-S. Kim

Abstract: A 24×24 slotted-waveguide array antenna is presented in the paper. The subarray concept is introduced to provide a broad reflection and gain bandwidth. A waveguide feed network is proposed to feed equal amplitudes and equal phases to the subarrays; it is composed of two layers, and is thus more compact and simpler than conventional feed networks. The subarray is made up of the feeding waveguide coupling slot, radiating waveguide and radiating slot. The measured reflection bandwidth is 5.5% (VSWR ≤ 2.0) and 9.5% (VSWR ≤ 2.7). The antenna gain varies within 2.1 dB over 4 GHz (9.5%). The maximum gain is 33.8 dBi at 41.5 and 42.5 GHz.

1 Introduction

Slotted-waveguide antenna arrays are attractive for many millimetre-wave radar and communication applications because of their low loss, high efficiency and flatness. These antennas may be either standing-wave or travelling-wave arrays of various radiating slots. Standing-wave arrays have a broadside beam at the centre frequency but a narrow reflection and gain bandwidth, while travelling arrays produce a broad reflection/gain bandwidth but have a tilted beam from the broadside at the off-centre frequency. In both arrays, the beam directions are frequency dependent.

The subarray concept was presented in [1, 2] to obtain a broad reflection/gain bandwidth while keeping a broadside beam direction. In [1], only the guidelines for the expected bandwidth improvements were described. More detailed geometries were provided in [2]. However, only a theoretical examination was conducted; experimental considerations were not included. Furthermore, the described array size in [2] was as small as 8×8. To design a large array using the array scheme shown in [2] – 24×24 or 32×32, for example – the feed network will require four or more layers. The coupling slot used in [2] was a series centre-inclined slot, which required a folded short circuit attached to the end of the feeding waveguide. Therefore, the array can become very complicated and the scheme described in [2] is not appropriate for larger arrays.

In this paper, a compact two-layer feed network is proposed to design a large 24×24 array antenna which provides a broad reflection and gain bandwidth for broadband multimedia wireless service (BMWS) applications over 40.5–43.5 GHz. The array consists of 4×4 subarrays, which have feeding waveguides, radiating waveguides, coupling slots and radiation slots. The feeding waveguides are milled in the bottom layer and the radiating waveguides are stacked above them. Longitudinal shunt slots are used for the coupling and radiation slots so that a folded short circuit is unnecessary. Therefore, the array scheme can be implemented with only two layers.

2 Subarray

A longitudinal slot in the broad wall of a rectangular waveguide is adopted as the coupling slot, as shown in Fig. 1*a*. The wave incident from port 1 on the feeding waveguide is coupled into the radiating waveguide through the coupling slot and propagates into ports 2 and 3. Figure 1*b* shows the geometry of the radiation slot; it is also a longitudinal shunt slot so that a folded short circuit is not required. A longitudinal slot is usually modelled as a shunt element, for which the equivalent normalised slot admittance Y can be obtained as follows [3]:

$$\frac{Y}{Y_0} = \frac{1 - \Gamma}{1 + \Gamma} \tag{1}$$

where Y_0 is the waveguide admittance and Γ is the reflection coefficient, which is obtained from a simulation with the aid of the finite element method tool, Ansoft's HFSS [4]. In this study, the slot is round-ended, 1.0 mm in width, 1.0 mm in thickness, and placed at a quarter guided wavelength from the shorted wall. A correction is usually applied for the round-end effects of the slot after the rectangular slot has been modelled [1], but in this study they are included in the simulation. Data for the self-admittance, resonant conductance, and resonant length against slot offset are obtained at several points from the HFSS simulation. Then, in the array design procedure, curve fits with polynomial expressions are used to extract more data.

Figure 2 shows the geometry of the subarray, which consists of a T-junction, two feeding waveguides, six radiating waveguides, four coupling slots, and 6×6 radiating slots. The width of the broad wall of the feeding waveguide is 4.7 mm, which is reduced from the width of

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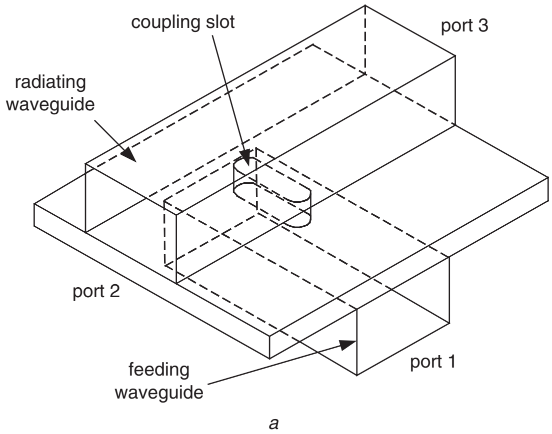

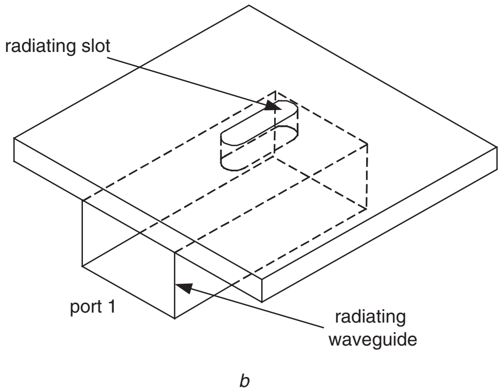

Fig. 1 *Geometry of slot*
a Coupling slot
b Radiating slot

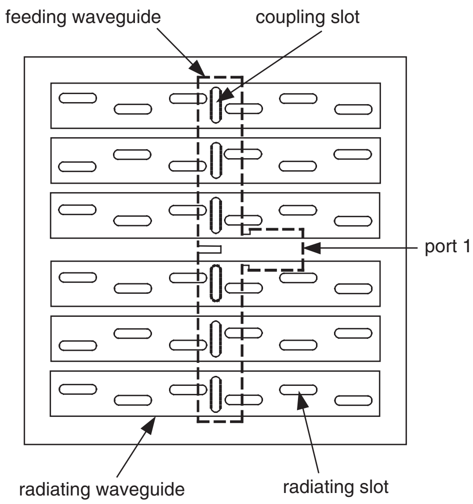

Fig. 2 *Geometry of subarray*

standard WR-22, 5.7 mm, since the thickness between the narrow walls of adjacent radiating waveguides must be >1.0 mm for the fabrication process. The height of the narrow wall of the feeding waveguide is 3.0 mm. The feeding waveguide is 4.7 mm in width and 2.85 mm in height. The length and offset of each radiating slot is determined using Elliott's design procedure [5, 6] and the data obtained from the simulations described in Figs. 1*a* and 1*b*. The centre-feed configuration is used, which increases the reflection bandwidth [7]. The designed T-junction has a low reflection coefficient below −25 dB over the desired frequencies and a 3-dB power splitting ratio.

Coupling slots are placed to provide an equal offset from the centreline of the feeding waveguide, as shown in Fig. 2, so that alternating-phase waves are fed into the radiating waveguides [8]. The surface currents on both sides of the narrow wall flow in opposite directions so that the total current across the contact vanishes. Therefore, perfect electrical contact between the waveguide and slot plate is unnecessary compared to in-phase feed schemes [9]. However, the antenna gain decreases because the nonuniformity of the radiating slot increases.

The subarray shown in Fig. 3 has been modelled using the HFSS simulator [4]. The magnitude of the return loss is shown, which has a broad reflection bandwidth of 4 GHz (9.5%) based on VSWR ≤2.0. The simulated gain patterns of the *E*-plane around the broadside at 40.5, 42.0 and 43.5 GHz are plotted in Fig. 4. The peak gain at all three frequencies is ∼22 dBi, and the largest difference between the values is only 0.4 dBi. Therefore, subarraying achieves almost the same peak gain over broad frequencies. This subarray is combined with the feed network in the following Section.

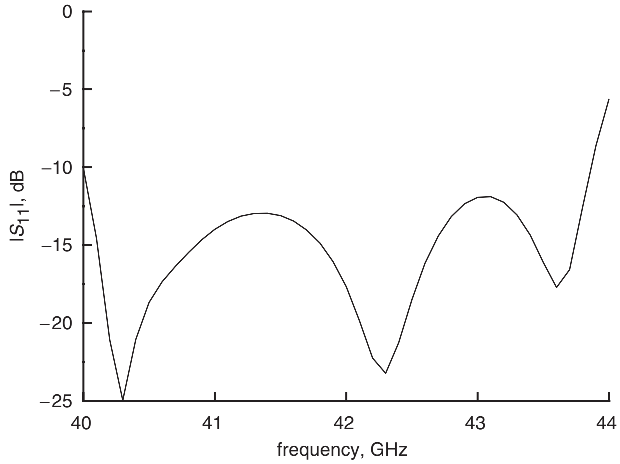

Fig. 3 *Simulated magnitude of return loss (S_{11}) of subarray*

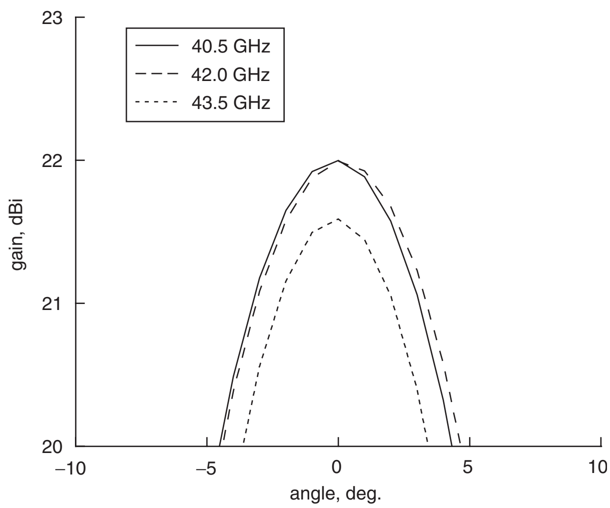

Fig. 4 *Simulated gain patterns around broadside of E-plane of subarray*

3 Feed network configuration

A corporate feed is an optimum method for feeding equal amplitudes and equal phases into subarrays over all frequencies. Three types of corporate feed networks are shown in Fig. 5, in which a small solid circle represents the coupling slot of the subarray shown in Fig. 3 and a solid line indicates the waveguide.

The first case, illustrated in Fig. 5*a*, is mostly used when implementing a corporate feed network with the microstrip line. It requires the smallest whole feeding paths of the three cases. However, as shown in the dotted circle A, the distance between the coupling slots within the circle is greater than one wavelength. Assuming that the width of the broad wall of the waveguide is 4.7 mm, this distance is 1.74 λ_0 or 12.4 mm ($=2.85+1.0+4.7+1.0+2.85$ mm), where 2.85 is the quarter guided wavelength and 1.0 is the marginal thickness between adjacent waveguides. A central spacing broader than one wavelength increases the side lobe level (SLL) [10] and thus decreases the antenna gain.

The second case, illustrated in Fig. 5*b*, does not have the above described problem. However, as shown in circle B, the spacing between adjacent feeding waveguides is so small that milling fabrication may be impossible. Furthermore, it is desirable that chokes are made to suppress leakage between adjacent waveguides [9], but spacing inside circle B does not allow it.

In this study, the third case, shown in Fig. 5*c*, has been used. The central spacing in circle A is not any broader than in the other cases. In circle B, the feeding waveguide is not dense and thus the milling process is possible and chokes can be placed between adjacent waveguides.

Figure 5*d* illustrates the simulation geometry for the corporate feed given in Fig. 5*c*. The numbers shown from 1 to 17 indicate the ports. The subarray of Fig. 3 will be attached to each port when the entire array is assembled. The WG-22 standard has been used for the input port 1. The T-junction used in the subarray of Fig. 3 has been adopted. The lengths d_1 and d_2 differ by a quarter guided wavelength to cancel the reflected waves from the T-junctions and the 90-degree *H*-plane bends because of

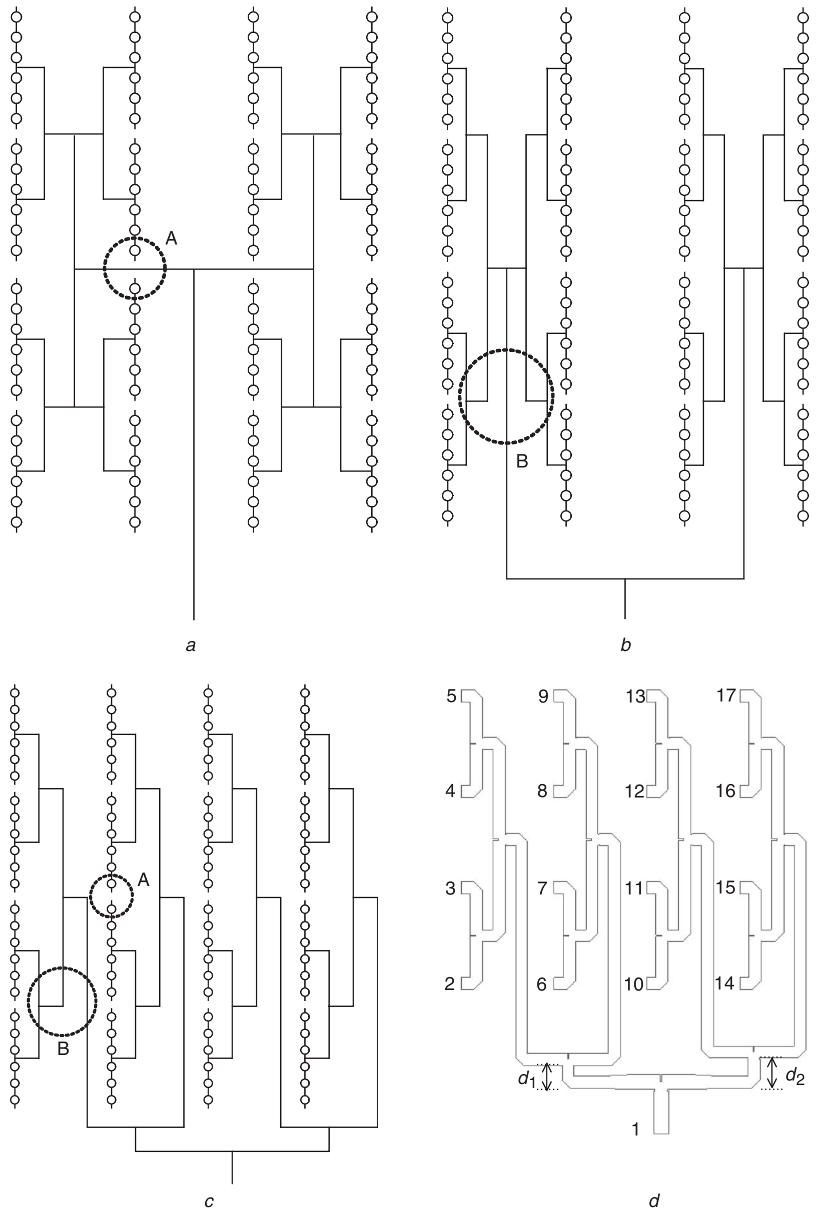

Fig. 5 *Three types of corporate feed networks*
a, *b* Failed schemes
c Proposed scheme
d Simulated geometry of Fig. 5*c*

the half-wavelength difference of the path. The simulation has been performed using the HFSS software, and the results are plotted in Figs. 6 and 7. The return losses in the desired frequencies are mostly below -15 dB, as shown in Fig. 6. The magnitude and phase of the transmission coefficients from input port 1 to the other 16 ports are depicted in Figs. 7*a* and *b*, respectively. The variation of magnitude is within 0.3 dB, which is tolerable in a large array. The phases of the transmission coefficients are almost identical.

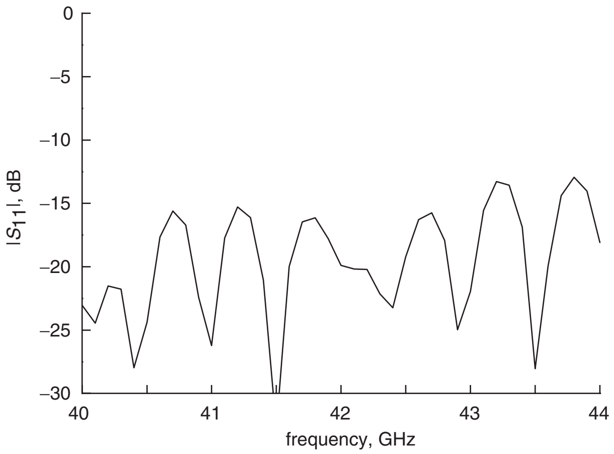

Fig. 6 *Simulated magnitude of return loss (S_{11}) of feed network*

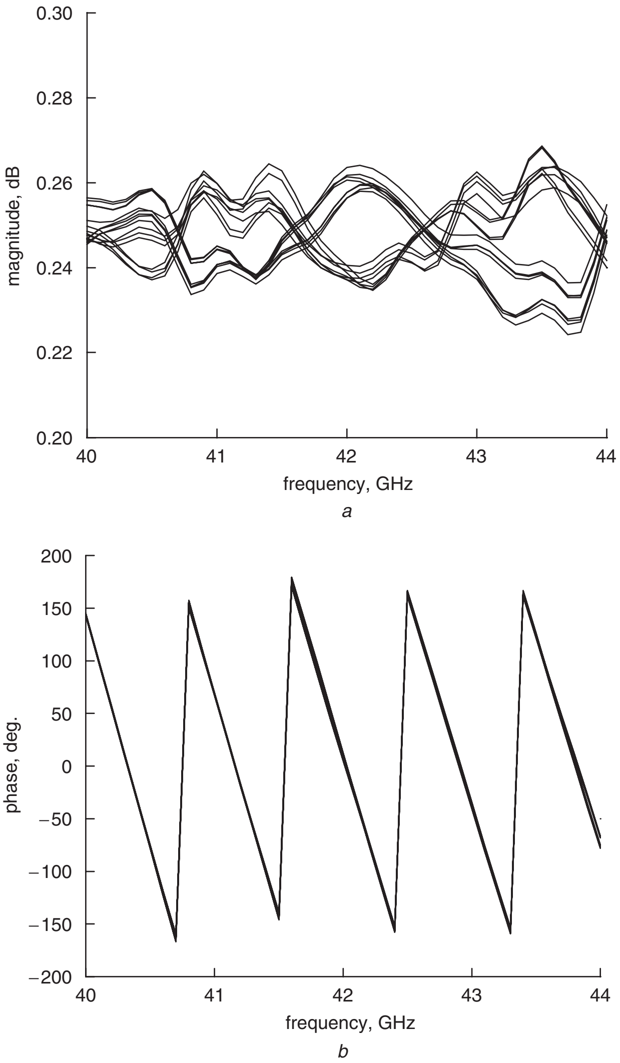

Fig. 7 *Simulated transmission coefficient*
a Magnitude
b Phase

4 Measured results

The 24×24 antenna array has been configured by combining the subarray of Fig. 3 and the feed network of Fig. 9, and has been fabricated using a milling process. Figure 8 shows photographs of the fabricated antenna. The radiating slot area is $13.8 \times 14.2\,cm^2$. Figure 8*a* shows the feeding waveguides. Chokes [9] are grooved along and beside the feed network. They act as short circuits along the waveguide upper corner and therefore suppress leakage. Figures 8*b* and 8*c* show the radiating waveguides and the entire assembled antenna, respectively. Figure 8*d* is the entire assembled antenna with the top-mounted radiating slots. Metallic screws have been used to join the waveguide plates and the slot plates.

The measured magnitude of the return loss is shown in Fig. 9. The bandwidth of return loss based on VSWR ≤ 2.0 is ~ 2.3 GHz (5.5%), and that based on VSWR ≤ 2.7 is >4.0 GHz (9.5%). Around the centre frequencies, very good return losses of dB are shown, especially -28 dB at 41.6 GHz, which comes from the quarter guided-wavelength difference between d_1 and d_2 illustrated in Fig. 5*d*. The deterioration around 43 GHz might be due to the fabrication tolerance, especially, at the T-junctions and slots. An overdesigned T-junction with a return loss of ~ -40 dB may overcome the fabrication tolerance. Even if the chokes were used, imperfect contacts between the waveguides and the slot plates might also affect the return loss characteristics. It must be noted that the thickness of the coupling and radiating slot plates is 1.0 mm because of the limit of our fabrication, but if the thinner plates are used, the *Q*-factor of the slot decreases, and the bandwidth of the return loss could broaden.

The measured radiation patterns at 40.5, 42.0 and 43.5 GHz are shown in Fig. 10. The SLLs are ~ -12 dB at three frequencies, which satisfies the SLL of the equal-amplitude feeding array. However, as the frequency keeps away from the centre frequency, there are several high sidelobes between 10° and 80°. The reason may be due to a subarray scheme shown in Fig. 2 where three radiating slots are placed in both sides. In the centre frequency, the radiating waves are in-phase, while at off-centre frequencies, phase differences among three slots exist. The second reason may be the *Q*-factor of the slot, and the relatively thick slot plates further increase the *Q*-factor. The *E*-plane has a larger SLL than that of the *H*-plane, which is caused by the displaced slot position in the *E*-plane, as shown in Fig. 8*d*. The beamwidths are $\sim 2.2°$ with a maximum variation of 0.7° among three frequencies. The measured antenna gain and aperture efficiency are shown in Fig. 11. The maximum gain is 33.8 dBi at 41.5 GHz and 42.5 GHz, which gives a very high aperture efficiency of 51%. The minimum gain is 31.7 dBi at both 41.0 GHz and 43.0 GHz. The gain variation over 4 GHz (9.5%) is within 2.1 dB, which is a very broad gain bandwidth.

5 Conclusions

A 24×24 slotted-waveguide array antenna was produced to provide a broad reflection and gain bandwidth. The subarray concept was introduced and the two-layer compact producible feed network was proposed. Our measurement results indicate a broad gain bandwidth of

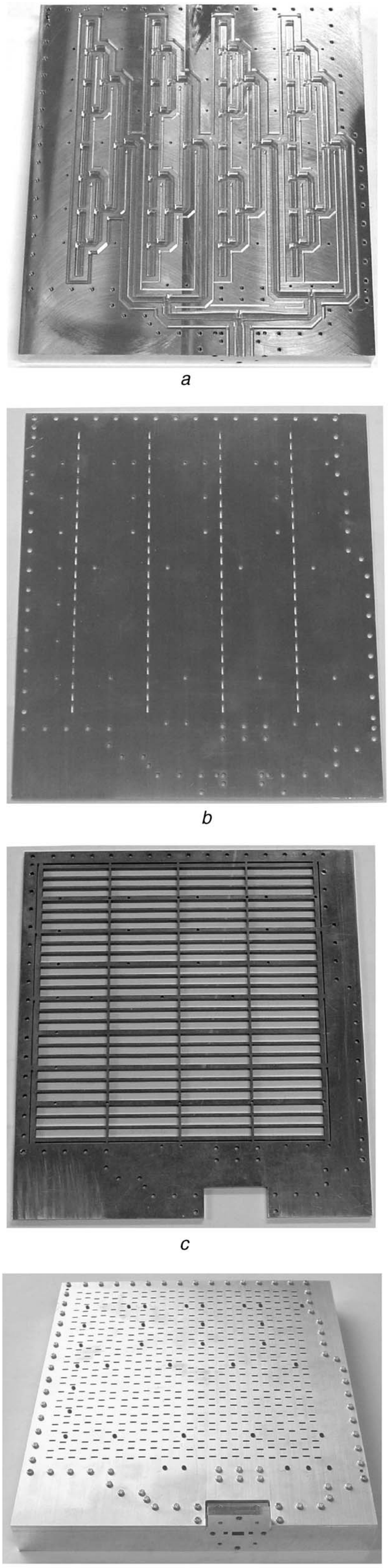

Fig. 8 *Photographs of fabricated 24 × 24 array*
a Feeding waveguide
b Coupling slot
c Radiating waveguide
d Assembled array

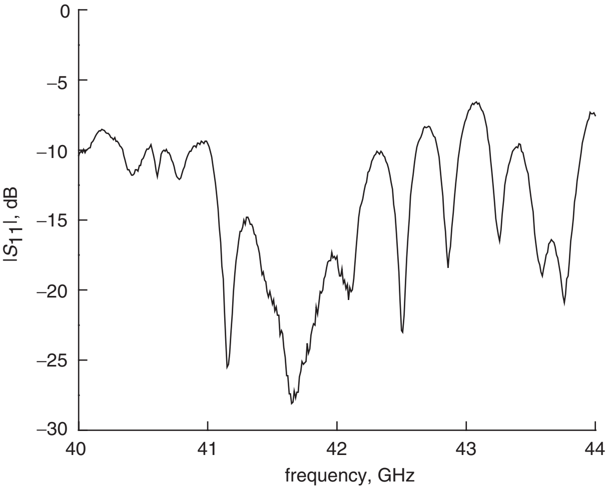

Fig. 9 *Measured magnitude of return loss (S_{11}) of the 24 × 24 array*

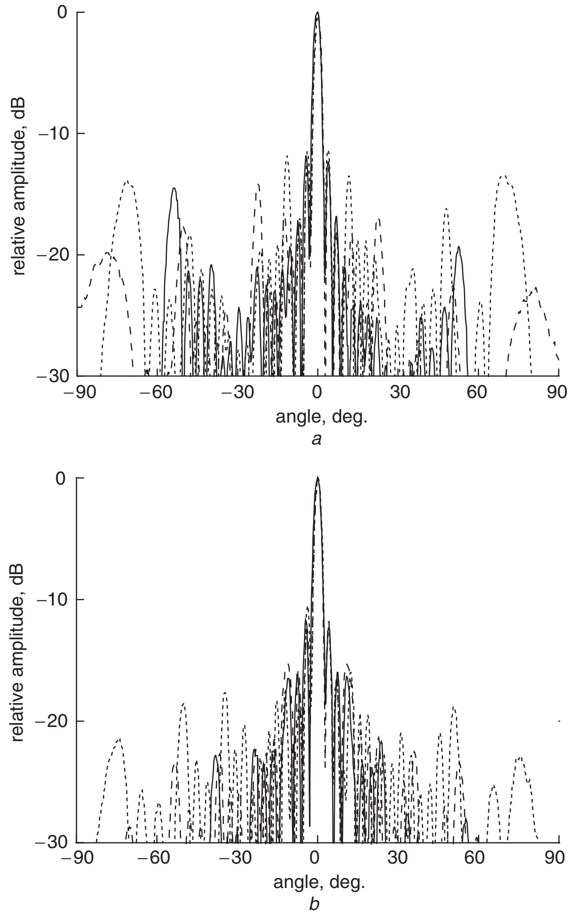

Fig. 10 *Measured radiation patterns*
a E-plane
b H-plane
—— 40.5 GHz - - - 42.0 GHz · · · · 43.5 GHz

∼9.5% with variation within 2.1 dB. The measured maximum gain is 33.8 dBi at both 41.5 and 42.5 GHz. The reflection bandwidth is ∼2.3 GHz based on VSWR ≤2.0, and >4.0 GHz based on VSWR ≤2.7. The SLLs are ∼−12 dB, and the 3-dB beamwidths are almost the same, at the desired frequencies. These results demonstrate that the 24 × 24 slotted-waveguide antenna array with a proposed two-layer feed network has a broad reflection/gain bandwidth, and it can be successfully applied to broadband millimetre-wave communications systems.

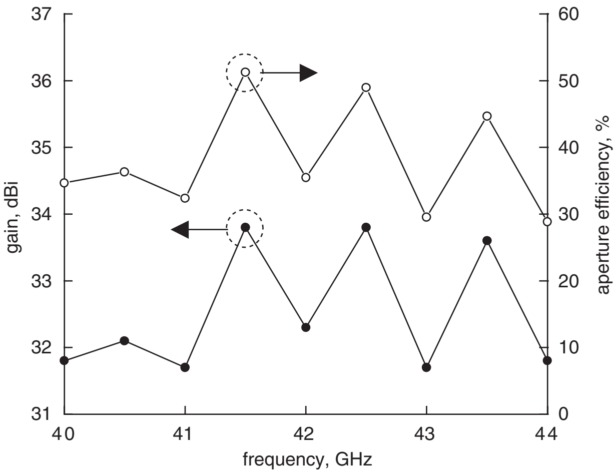

Fig. 11 *Measured antenna gain and aperture efficiency*

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